

Possible three-nucleon force effects in D–P scattering at low energies

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Abstract

We present measurements of the analyzing powers A_y and iT_{11} for proton–deuteron scattering at $E_{c.m.} = 432$ keV. Calculations using a realistic nucleon-nucleon potential (Argonne V18) are found to underpredict both analyzing powers by $\approx 40\%$. The inclusion of the Urbana three-nucleon interaction does not significantly modify the calculated analyzing powers. Due to its short range, it is difficult for this three-nucleon interaction to affect A_y and iT_{11} at this low energy. The origin of the discrepancy remains an open question.

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Few-body systems provide a fundamental testing ground for nuclear interactions. Comparisons of measured three-nucleon scattering observables to theoretical calculations allow stringent tests of the underlying nucleon-nucleon (NN) and models of the three-nucleon (3N) interactions. Past studies have found that rigorous calculations utilizing realistic NN potentials underpredict by 25-30% the measured analyzing power A_y in n-d scattering at low energies – a surprising discrepancy which has been dubbed the “ $A_y(\theta)$ puzzle” (see Ref. [1] and references therein). Precise calculations for p-d scattering [2,3] below the deuteron breakup threshold including the Coulomb potential rigorously have recently become possible to perform. These calculations find [3,4] that a similar underprediction exists here for A_y and also iT_{11} . The agreement for other observables, including cross sections, T_{20} , T_{21} , T_{22} , and n-d scattering lengths [5] is generally excellent. The analyzing powers A_y and iT_{11} in N-d scattering are known to be very sensitive to the NN potential in the 3P_j waves. It has been suggested that the potential in these waves may not be known to the necessary precision at low energies [6,7]. The possibility that the underprediction is due to 3N force effects has also been considered [1,3,4]. This paper investigates the roles of NN and 3N force effects on A_y and iT_{11} for N-d scattering; we do not consider here other possibly important effects such as relativistic corrections or subnucleonic degrees of freedom. We do note, however, that the Mott-Schwinger interaction, a long-ranged electromagnetic effect, has been recently shown *not* to be responsible for the discrepancies in A_y and iT_{11} [8].

Measurements of both A_y and iT_{11} are useful, as these observables depend on different combinations of phase shift and mixing parameters (principally in P -waves), and they also have been shown to be sensitive to different combinations of the 3P_j NN interactions [6]. The majority of the data on these analyzing powers has been obtained in the vicinity of the deuteron breakup threshold: n-d A_y data exist for $E_{c.m.} \geq 2$ MeV [9,10] p-d A_y data exist for $E_{c.m.} \geq 0.53$ MeV [11–13], and p-d iT_{11} data exist for $E_{c.m.} \geq 1.7$ MeV [12,13] (there are no n-d iT_{11} data). It is desirable to determine these observables at lower energies, as the influence of higher partial waves is strongly reduced, and the dominant S - and P -waves can be investigated with more confidence. In addition, as we will show below, P -wave N-

d scattering at low energies is almost entirely determined by the asymptotic part of the three-nucleon scattering wave function and the NN interaction. Under these conditions the connection between the measured observables and the underlying interactions is greatly simplified. The calculated analyzing powers A_y and iT_{11} are mainly determined by the j -splitting of the P -wave N-d phase shifts and the $\varepsilon_{3/2}^-$ and $\varepsilon_{1/2}^-$ mixing parameters. Due to the angular momentum barrier at low energies, these observables are very small and difficult to determine experimentally. This paper reports measurements of A_y and iT_{11} for p-d elastic scattering at $E_{c.m.} = 432$ keV. These data are at the same energy as our previously-reported T_{20} and T_{21} measurements [5].

These experimental results are compared to calculations utilizing the Pair-Correlated Hyperspherical Harmonic (PHH) basis [14] to construct the scattering wave function, and the Kohn variational principle to determine the scattering matrix elements [2]. In addition, we present calculations using an “optimized” Born approximation [4] for the peripheral partial waves. The calculations have been done using the AV18 potential [15] and with AV18 plus the 3N interaction of Urbana (UR) [16]. It has been shown in Ref. [1] that other high-quality NN potentials such as Bonn or Nijmegen predict essentially the same n-d A_y just below the deuteron breakup threshold, so we would not expect our conclusion to change if these potentials were used.

The measurements were performed using polarized proton and deuteron beams from the atomic beam polarized ion source [17] at the Triangle Universities Nuclear Laboratory. The deuteron beams were accelerated to $E_d = 1.3$ MeV using the FN tandem accelerator, and then directed into a 62-cm diameter scattering chamber. Proton beams were accelerated into a 107-cm diameter scattering chamber at $E_p = 650$ keV using the minitandem accelerator [18] and chamber bias voltage [19]. Thin hydrogenated or deuterated carbon targets were utilized which consisted of approximately 1×10^{18} and 1.5×10^{18} hydrogen isotope and carbon atoms/cm², respectively. The beams lose ≈ 10 keV in these targets, with an average energy of $E_{c.m.} = 432 \pm 1$ keV for both measurements. The use of thin targets is very important at low energies for minimizing energy loss and straggling effects.

The proton beam polarization was determined using the ${}^6\text{Li}(\vec{p}, {}^3\text{He}){}^4\text{He}$ reaction in a polarimeter [20] located at the rear of the scattering chamber. The polarization was measured several times throughout the measurements at an incident proton energy of 450 keV by lowering the chamber bias voltage. The proton polarization was found to be constant within $\pm 3\%$ throughout the measurements; the systematic error in the proton polarization is estimated to be $\pm 4\%$. Deuteron beam vector polarization was determined online via the ${}^{12}\text{C}(\vec{d}, p)$ reaction in a polarimeter located behind the scattering chamber. The effective iT_{11} for this reaction at $E_d = 1.3$ MeV has been calibrated relative to the ${}^3\text{He}(\vec{d}, p)$ reaction in another polarimeter at $E_d = 12$ MeV [21]. The absolute uncertainty in the deuteron beam polarization is estimated to $\pm 3\%$. For both beams the data were taken with the spin-quantization axis perpendicular to the reaction plane, using two spin states with $p_z \approx \pm 0.7$ for the proton beam; and $p_z \approx \pm 0.55$, $p_{zz} \approx 0$ for the deuteron beam. The spin states were cycled approximately once every second, in order to minimize the effects of slow changes in beam position, target thickness, or amplifier gain.

Scattered deuterons and protons were detected in coincidence using two pairs of silicon surface barrier detectors placed at symmetric angles on either side of the incident beam. The angles of the detectors were set to observe either protons or deuterons in the more forward detectors in coincidence with deuterons or protons detected in the more backward detector on the opposite side of the beam. Histograms of the time difference between the fast timing signals from each coincident pair of detectors were stored for each spin state. Dead-time corrections ($< 3\%$) were determined by sending test pulses to the detector preamplifiers with time delays adjusted to give distinct peaks in the time spectra. The time resolution for the coincident proton-deuteron peaks was ≈ 10 ns, with backgrounds $< 3\%$. The analyzing powers were determined from the counts in the coincident peaks, after correction for background, dead time, and the number of incident particles (determined by beam-current integration). It should be noted that the coincidence technique is essential for measuring the small analyzing powers A_y and iT_{11} with these targets, as the elimination of carbon elastic-scattering events by the fast coincidence requirement allows proton-deuteron scatter-

ing events to be counted at the high rate required to achieve reasonable statistical accuracy. The results for A_y and iT_{11} are shown in Fig. 1. The error bars include contributions from statistics and background subtraction, but not the absolute beam polarization.

The theoretical method has been described previously [2,3]; it can be applied equally well to n-d as well as p-d scattering, and realistic NN and 3N potentials can be used without difficulty. In the present calculations, scattering waves with orbital angular momentum up to $L = 4$ have been taken into consideration. At this energy, the differential cross section, A_y , and iT_{11} are determined almost entirely by waves with $L \leq 1$, while for T_{20} , T_{21} , and T_{22} $L = 2$ waves are also important. In particular, A_y and iT_{11} change by $< 10^{-4}$ when phases with $L > 1$ are considered. In Fig. 1 the data are compared to the calculations using the AV18 potential and the AV18+UR potential. The corresponding P -wave and $^4S_{1/2}$ phase-shift parameters are given in Table I.

It is seen that both calculations underpredict the data by $\approx 40\%$. The change in the calculated A_y and iT_{11} resulting from the inclusion of the 3N interaction is too small *by an order of magnitude* to explain the discrepancy.

Relatively small changes in the N-d phase shift parameters can have large effects on the corresponding analyzing powers. In Ref. [4] it was found that the discrepancies in A_y and iT_{11} for $E_{c.m.} = 1.67$ and 2 MeV could be corrected by reducing the $^4P_{1/2}$ phase shift by 3.4% and increasing the absolute value of $\varepsilon_{3/2}^-$ mixing parameter by 12%. Using the AV18+UR results for the other phase-shift parameters, we find that agreement with our A_y and iT_{11} results is optimized if the $^4P_{1/2}$ and $\varepsilon_{3/2}^-$ parameters given in Table I (column 2, in parenthesis) are replaced by 5.22° and -1.02° , i.e., the absolute values are reduced by 1.6% and increased by 15%, respectively. The results for A_y and iT_{11} using these parameters are shown by the long-dashed curve in Fig. 1. It is important to note that these parameter changes affect the cross section by $< 0.15\%$, and the other analyzing powers by < 0.0012 . In particular, the good agreement observed previously with our T_{20} and T_{21} data at this energy [5] is not disturbed. While similar to the changes required at higher energies [4], there are significant differences in the fractional changes required. We should point out

however that there is no reason to expect the percentage change required to be the same for different energies.

We have also performed calculations using an “optimized” Born approximation, i.e., the procedure in which the second-order \mathcal{R} -matrix is estimated using the asymptotic part of the three-nucleon wave function as described in Ref. [4]. The results for the $^4S_{3/2}$ and P -wave phase-shift parameters are given in Table I and compared to those obtained when the complete wave function is considered (full solution). It is seen that the Born approximation results are close to the full calculation for these partial waves. In the case of the $^4S_{3/2}$ phase the Pauli principle prevents the three particles from being close to each other, while for the P -waves the centrifugal barrier is sufficiently high at these energies. These findings indicate that these partial waves are almost entirely determined by the asymptotic structure of the system. We also show in Table I the results for the full solution and Born approximation at $E_{c.m.} = 2$ MeV, where it is seen that the accuracy of the Born approximation for low partial waves is reduced. On the other hand we observe that the influence of the 3N force is small and of the same magnitude at both energies.

The small effect on A_y and iT_{11} from including the UR 3N interaction is now clear. This interaction, which is based on two-pion exchange and includes a phenomenological repulsive short range term, requires the three nucleons to be close together in order to produce a significant effect. The likelihood for this situation is diminished by the diffuse structure of the deuteron which results from the small binding energy. For low energy p - d scattering in P -waves (or higher L values), the probability of finding three nucleons in close proximity is further reduced by the centrifugal and Coulomb barriers. We thus draw the important conclusion that 3N interactions based on two-pion exchange cannot produce significant changes in A_y and iT_{11} at low energies.

Other choices for the 3N potentials, such as the Tucson-Melbourne [22] or the Brazil [23] models, give quite similar conclusions. Inclusion of other processes, such as $\pi - \rho$ or $\rho - \rho$ exchanges, involving heavier mesons and therefore shorter ranges, are expected to give still smaller corrections [1]. These findings thus indicate that new types of 3N interactions should

be considered. One possibility is the inclusion of a spin-orbit 3N force which could significantly affect the N-d P -waves [24]. One cannot exclude also the possibility that inadequacies in the NN interaction are responsible for the discrepancy.

In summary, our measurements of A_y and iT_{11} at $E_{c.m.} = 432$ keV are significantly underpredicted by calculations utilizing the AV18 NN interaction. The inclusion of the UR 3N interaction does not significantly change the theoretical calculations. We have shown it is difficult to identify a 3N interaction which could significantly change these analyzing powers at low energies, as they are mainly determined by long-ranged interactions. It would be of great interest to extend these comparisons to p- ^3He and n- ^3H scattering, where the 3N force effects are expected to be larger, as the likelihood of finding three nucleons close together is enhanced by the tighter binding of ^3H and ^3He .

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FIGURES

FIG. 1. Experimental A_y and iT_{11} for p-d scattering at $E_{c.m.} = 432$ keV (circles), along with theoretical calculations using the AV18 (solid line) and the AV18+UR potentials (short-dashed line). The long-dashed line results from modifying the ${}^4P_{1/2}$ and $\varepsilon_{3/2}^-$ phases as described in the text.

TABLES

	$E_{c.m.} = 0.432 \text{ MeV}$		$E_{c.m.} = 2 \text{ MeV}$	
	Born	Full	Born	Full
$^4S_{3/2}$	-28.9 (-28.9)	-28.2 (-28.2)	-55.3(-55.3)	-63.1 (-63.1)
$^2P_{1/2}$	-2.16 (-2.16)	-2.01 (-2.01)	-9.09(-9.10)	-7.36 (-7.37)
$^4P_{1/2}$	4.76 (4.76)	5.30 (5.30)	18.5(18.5)	22.1 (22.3)
$\varepsilon_{1/2}^-$	1.64 (1.65)	2.45 (2.50)	3.31(3.33)	5.71 (5.83)
$^2P_{3/2}$	-2.15 (-2.15)	-1.99 (-1.99)	-8.91(-8.93)	-7.14 (-7.15)
$^4P_{3/2}$	5.40 (5.39)	6.16 (6.17)	20.6(20.6)	24.2 (24.2)
$\varepsilon_{3/2}^-$	-0.574(-0.573)	-0.861(-0.888)	-1.40(-1.40)	-2.20 (-2.23)
$^4P_{5/2}$	5.23 (5.23)	5.78 (5.79)	20.5(20.5)	23.9 (24.1)

TABLE I. Some of the theoretical phase shifts and mixing parameters (in degrees) calculated at $E_{c.m.} = 0.432$ and 2 MeV for the AV18 potential; the values in parentheses correspond to the AV18+UR potential. For both energies, the results for the “optimized” Born approximation and the full solution are reported in the columns labeled “Born” and “Full”, respectively.

